Air-Ground Heterogeneous Networks for 5G and Beyond via Integrating High and Low Altitude Platforms

Junfei Qiu, David Grace, Guoru Ding, Muhammad D. Zakaria, and Qihui Wu

Abstract

Unmanned aerial vehicles (UAVs) are expected to be an important complementary component for 5G (and beyond) communication systems to achieve the goal of global access to the Internet for all. To fully exploit the benefits of distinct features of various UAVs, this article proposes a novel hierarchical network architecture enabled by software defined networking, which integrates cross-layer *high and low altitude platforms* into conventional terrestrial cellular networks to inject additional capacity and expand the coverage for underserved areas in a flexible, seamless, and cost-effective manner. Specifically, we first present a comprehensive comparison and review on different types of UAVs for communication services. Then, we propose an *integrated air-ground heterogeneous network* architecture and outline its characteristics and potential advantages. Next, several key enabling techniques for the integrated system are discussed in detail. In addition, we identify the potential application scenarios where the system can further enhance the performance of the traditional terrestrial networks, followed by the case study to demonstrate the effectiveness of the proposed architecture. Finally, the discussions on challenges and open research issues are given.

I. Introduction

Striving to provide universal and affordable access to the Internet has been enshrined by the United Nations (UNs) as one of the 17 sustainable development goals in the 2030 Agenda for Sustainable Development [1]. Fifth generation (5G) cellular networks have been regarded as the dominant technology to deliver worldwide connectivity in the forthcoming years. However, to achieve ubiquitous coverage for anyone, anywhere at any time in a real sense, a number of challenging barriers still need to be tackled. For instance, since network deployments for mobile operators are business and profit-driven, *rural and remote areas* with low population densities and limited income are less appealing for operators to install 5G sites. In such areas, it is hard to generate sufficient revenue for operators to compensate for their capital

Junfei Qiu, David Grace, and Muhammad D. Zakaria are with University of York; Guoru Ding is with Army Engineering University; Qihui Wu is with Nanjing University of Aeronautics and Astronautics.

expenditure (CapEx) and operational expenditure (OpEx). In addition, for some *hotspot areas* such as the Olympic Games venues, traffic demands will temporarily far exceed the capacity density of the ground cellular networks. In this case, further considering deploying new base stations on a permanent basis is not economically feasible. Besides, in *emergency* situations such as natural disasters, terrestrial networks may be destroyed, meaning that fast communication service recovery is hard to provide as it is not practical to install new 5G infrastructure immediately.

To deal with the aforementioned issues, research on employing unmanned aerial vehicles (UAVs) in wireless communication systems has reached an unprecedented peak recently [2], due to their superior attributes such as mobility, flexibility, and adaptive altitude. They can offer a valid alternative and an efficient complement to traditional terrestrial or satellite-based infrastructure, acting as either aerial user terminals to provide such as information dissemination and data collection, or as flying base stations to enhance coverage and capacity of wireless networks. Although there have been many discussions on utilizing UAVs in cellular networks in the existing recent works [3], most just focus on low-altitude UAVs (i.e., low altitude platforms, which typically operate at an altitude not exceeding several kilometers), while neglecting the potential usage of high-altitude UAVs (i.e., high altitude platforms, which operate at the stratospheric altitudes in typically quasi-stationary locations)[1]. Generally speaking, *low altitude platforms* (LAPs) are more cost-effective and can be more swiftly deployed than *high altitude platforms* (HAPs), but HAP-based communications also have several important advantages such as wider coverage and longer endurance. In fact, the sundry assets of UAVs and their placement options provide a unique potential to create multi-tier heterogeneous aerial networks [4] to inject additional capacity and expand the coverage for 5G terrestrial networks.

Motivated by the above observations, different from existing works focusing on standalone aerial networks, in this article, we investigate exploiting the latent opportunities and challenges for integrating both HAPs and LAPs into 5G and beyond (B5G) cellular systems. Specifically, we first summarize the main characteristics of HAPs and LAPs for the provision of communication services. Next, an integrated HAP-LAP-terrestrial heterogeneous network architecture based on software defined networking (SDN) is proposed with discussions about the motivation and feasibility for integration and its potential advantages. In the following section, several key enabling technologies associated with the operation of the integrated air-ground networks are identified. Then we introduce several potential application scenarios. Moreover, the performance gain of the proposed integrated architecture is demonstrated via a preliminary case study. Finally, the challenges and open issues are given, followed by the conclusion of this work.

[1]In this article, the term "UAV" is a general concept covering the various aerial platforms such as drones, airships, aircraft, balloons, etc.

TABLE I

TYPICAL FEATURES COMPARISON OF HAPS AND LAPS FOR COMMUNICATION SERVICES.

Aerial platforms	Key features	Classification type	Typical performance and specification						Challenges and opportunities for integrating into 5G/B5G
			Payload capabilities	Mobility and station keeping	Power source and endurance	Data rate and capacity	Radio frequency transmit power	Main applications	
High altitude platforms (HAPs)	HAPs are aerial unmanned long-endurance platforms situated at the stratospheric altitudes which can provide multipurpose communications payloads over regional areas of coverage.	Aircraft	<150kg/<500W	Usually fly on a tight circle (about 2 km radius or more)	Solar cells (+fuel cells), 1∼3 months	High, capacity can upgrade by increasing the number and changing the size of the spot beams	1∼5 W for per cell	Wide area relay and broadcast, environmental monitoring, maritime surveillance, earth observation, internet connectivity	• **Pros:** Wider coverage and longer endurance; high payload capabilities; capacity increases through spot-beam resizing; have licensed spectrum • **Cons:** Deployment cost is a little high; challenging for maintaining station-keeping
		Balloon	<100kg/<100W	Most are stationary (Google Loon can move with the wind speed)	Fuel cells (+solar cells), 1∼3 months				
		Airship	<500kg/<5∼6kW	Quasi-stationary (only need to compensate for the winds)	Solar cells (+fuel cells), 1∼several years				
Low altitude platforms (LAPs)	LAPs typically refer to small fuelled unmanned airplane, having short mission durations and operating at generally modest or low altitudes.	Fixed-wing	Heavy payload, in general up to 100 kg	High speed, maximum speed with 120 km/h, must maintain continuous forward motion to remain aloft	Fuel cells (+solar cells), up to dozens of hours, will be longer with solar power	Relatively low, limited by the platform size	0.1∼5 W in general	Emergency communication, military surveillance, caching relay nodes, aerial inspection, temporary events support	• **Pros:** Cost-effective, light weight and more swiftly deployed; short-range line-of-sight (LoS) communication links, closer to mission objectives; good wireless connectivity • **Cons:** Low payload and endurance; limited flight time
		Rotary-wing (helicopter)	Low, depends on size, in general 30∼50 kg	Medium speed, 15∼40 km/h, can stay stationary in the air	Battery-powered, up to several hours, will be longer if tethered to the ground				
		Rotary-wing (multicopter)	Low, depends on size, in general 10∼15 kg	Limited mobility, are able to move in any direction as well as to stay stationary in the air	Battery-powered, up to several hours, will be longer if tethered to the ground				

II. HAPS VS. LAPS FOR COMMUNICATION SERVICES

In this section, we mainly provide a comprehensive review and comparison on the existing state-of-the-art developments in HAPs and LAPs for communication services. Table 1 summarizes the typical features of HAPs and LAPs, and Table 2 introduces several well-known projects/products of utilizing UAVs to serve communication applications.

HAPs are aerial unmanned long-endurance platforms situated in the stratosphere (from 17 to 22 km) which can provide multipurpose communications payloads over regional areas of coverage, without the need for significant and expensive ground based infrastructures [5]. HAPs for telecommunications were studied extensively in 1990s and 2000s. However, owing to the technology limitations, particularly relating to the solar cell, battery and aeronautics, very few research projects continued. Fortunately, with the improvement of key enabling technologies of materials, battery and energy capture in recent years, accompanied by ample capital investment from several major Internet companies like Google and Facebook, the development of HAPs has been back in the public eye. In contrast to satellites, HAPs have better link budget and higher capacity, lower propagation delays, lower upgrading cost, and shorter landing and takeoff times for maintenance purposes. They have been considered as new radio access platforms for the 5G wireless communication system by the Third Generation Partnership Project (3GPP) [6]. Moreover,

TABLE II

SEVERAL WELL-KNOWN PROJECTS/PRODUCTS FOR HAPS AND LAPS.

Projects/Products	Description	Leading organizations	Start time
Zephyr (http://www.airbus.com/defence/uav/zephyr.html)	Zephyr is a high altitude pseudo-satellite, running exclusively on solar powe r with a goal of filling a capability gap between satellites and low-altitude UAVs.	Airbus Defense and Space	2013
Project Loon (https://x.company/loon/)	Project Loon is a network of stratospheric balloons at altitudes between 18 km and 25 km, travelling on the edge of the space to provide Internet access for rural and remote areas worldwide.	Google	2012
Aquila (https://code.facebook.com/posts/268598690180189)	Aquila is a solar-powered high-altitude aircraft, intended to act as relay stations to connect areas of the world that traditionally haven't had reliable internet access.	Facebook	2014
StratoBus (http://airstar.aero/en/technologies-for-stratobus/)	Stratobus is an autonomous airship, operating at an altitude of about 20 kilometers with stationary position to carry out a wide range of missions, including observation, security, telecommunications, broadcasting and navigation.	Thales Alenia Space	2010
Skybender (https://www.theguardian.com/technology/2016/jan/29/project-skybender-google-drone-tests-internet-spaceport-virgin-galactic)	Project SkyBender aims to beam 5G internet from solar-powered drones, which is expected to use new millimeter wave technology to deliver data from drones – potentially 40 times faster than 4G.	Google	2016
Flying Cell on Wings (CoW) (http://about.att.com/innovationblog/cows_fly)	Flying CoW is a cell site on a drone, aiming to beam LTE coverage from the sky to customers on the ground during disasters or big events.	AT&T Company	2017

in April 2018, the North Sky Research (NSR) of United States has released a comprehensive analysis report of the HAPs market, which claims that the global HAPs revenue will keep increasing in the next ten years[2].

Compared with LAPs, HAPs have longer endurance since most of them are solar-powered. Furthermore, HAP systems are typically preferred for providing coverage for larger geographic areas. For instance, the HAP coverage radius can be up to 200 km, while it is just within hundreds of meters for LAPs. Besides, a HAP can achieve cell coverage through *spot beams* delivered by a phased array antenna without using any infrastructures [5]. Moreover, since the size of the spot beam can be optionally adjusted, amorphous cells with flexible capacity provision will be available just through resizing the spot beam. In addition, the International Telecommunication Union (ITU) has released various frequency ranges for HAP applications, such as 47-48 GHz band worldwide on the secondary basis shared with satellites, 28-31 GHz for broadband services and 2.1 GHz for the provision of mobile communication services to users [7]. However, HAPs are more expensive and the deployment time is longer than LAPs. At the same time, they also have to maintain station and the stabilization of the on-board antenna. Besides, since the HAPs operate in the stratosphere for serving communication applications, some environmental conditions such as rain attenuation may interfere the system performance.

On the other hand, compared to HAP-based communications, wireless communications with LAPs (typically referred to small fuelled unmanned airplanes, have short mission durations and operate at an

[2]http://www.nsr.com/research-reports/satellite-space-infrastructure/high-altitude-platforms-haps-market-2nd-edition/, High Altitude Platforms (HAPS), 2nd edition, 2018.

altitude not exceeding several kilometers) have been also receiving considerable attention from the research community recently, due to their flexible mobility, preferable link budget and cost-effective maintenance features. Firstly, the deployment of LAPs can be swift thus making them more appropriate for unexpected or limited-duration missions (e.g., emergency situations). Moreover, LAPs can provide significant coverage improvement due to higher LoS connections. However, the hover and flight time is limited for the LAPs due to the constraint of on-board energy, which means that LAPs are unable to provide long-term and continuous wireless coverage. Besides, a shortage of dedicated licensed spectrum means that LAPs always need to coexist with existing terrestrial systems using shared spectrum.

To sum up, in terms of HAP and LAP, each one has its specific advantages and drawbacks. However, if considering leveraging the strength of both sides, several key issues will arise, such as: 1) how to design an efficient architecture to integrate both HAPs and LAPs into terrestrial cellular systems, forming a heterogeneous air-ground network? 2) what opportunities and challenges will such an architecture bring? and 3) where are the potential and typical application scenarios for the integrated system? The following sections of this paper will shed light on the aforementioned queries and provide some research insights.

III. Integrated Air-Ground Network Architecture via Leveraging HAPs and LAPs

To fully capitalize on the potential benefits of different types of UAVs, in this section, we propose an *integrated air-ground heterogeneous network* architecture, investigating how HAPs and LAPs can collaborate to provide enhanced coverage and capacity for the underserved areas.

A. Motivation and Feasibility for the Air-Ground Network Integration

Broadband access everywhere constitutes a pillar of 5G and B5G service requirements, however, standalone 5G terrestrial networks have many challenges to meet such a target, as detailed in the following.

- Dense terrestrial network deployment for rural and remote areas is not practical, due to the high cost of infrastructure, leading to a poor coverage for these regions.
- Even though current mobile networks can actually be reconfigured when load and capacity demands change in certain areas (cells), conventional terrestrial networks are still not efficient enough to deal with some temporary emergency or overloaded cases.
- The maximum coverage diameter is another challenge for terrestrial base stations. For instance, millimeter wave (mmWave) is one of the principle approaches for 5G, however, due to the higher path loss at the mmWave band this inevitably reduces the coverage to smaller areas. Moreover, for a Long-Term Evolution (LTE) macrocell base station, the coverage diameter is just several kilometers, while that is even less than hundreds of meters for a small cell.

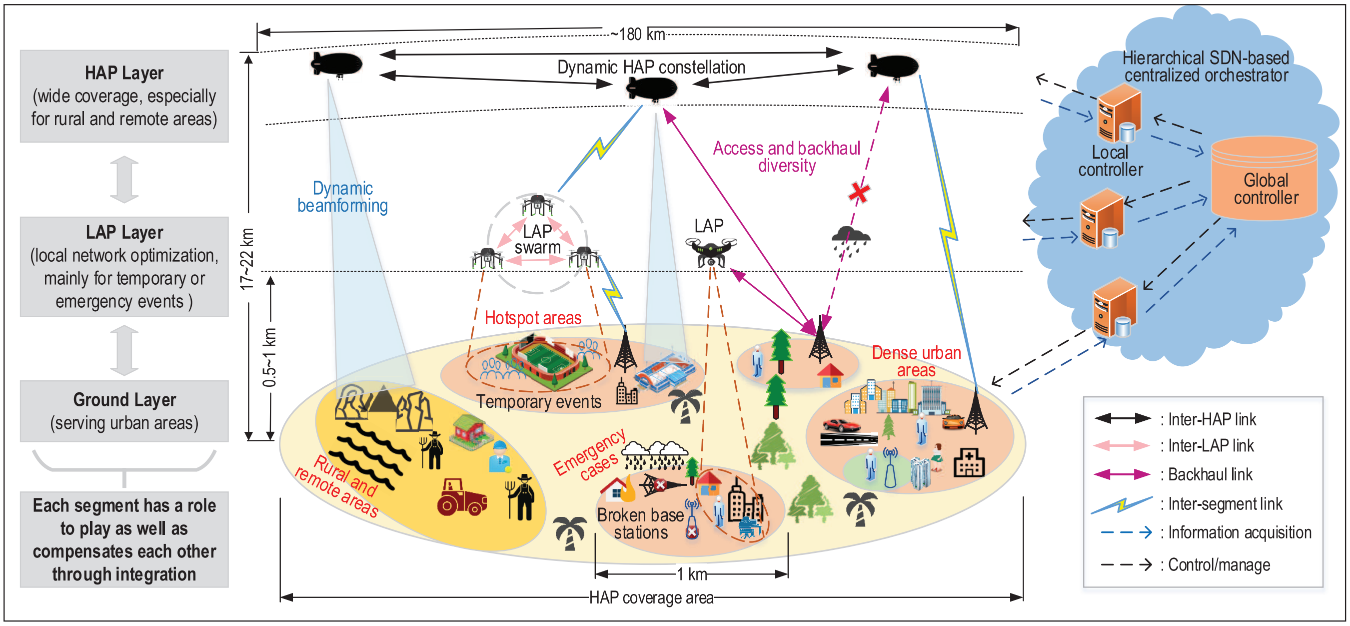


Fig. 1. Hierarchical integrated air-ground network architecture.

Since there is no single one-size-fits-all solution that can effectively satisfy all the needs of universal Internet access, global service provision will likely need the interworking of multiple heterogeneous wireless technologies. In the regions where providing a desirable terrestrial assistance is not efficient, various types of aerial platforms can act as a viable alternative to improve performance, agility, and flexibility of 5G and beyond mobile networks in unprecedented ways [8]. Through integrating HAPs and LAPs into conventional terrestrial networks, the benefits from both air and ground segments can be fully exploited to support multifarious communication services and scenarios.

B. Integrated HAP-LAP-Terrestrial Hierarchical Network Architecture

Fig. 1 shows the proposed hierarchical integrated air-ground system architecture for B5G wireless networks. The integrated network comprises three main segments: *HAP, LAP and ground layers*. A centralized orchestrator based on SDN is also embedded into the system to manage the operation of the whole system at the upper level. The characteristics for each constituent part are summarized as follows:

• **HAP layer:** The HAPs are expected to operate at the stratospheric altitude to deliver LoS connectivity over a large geographical area. They are capable of harvesting and storing solar energy, allowing them to stay aloft for a long period to provide continuous service. A single HAP can establish a wide variety of cells with centralized and flexible capacity provision (the cell sizes may be reduced to provide increased capacity) by using phased array antennas to generate multiple spot beams to simultaneously serve several different areas. This advantage can help HAPs to reduce the end-to-end latency[3] and deliver communication coverage anywhere within the service area without moving their positions. Moreover, a dynamic constellation of HAPs can be formed to provide extended communication coverage and increased capacity density. Besides, with the advantages of high altitude, long endurance and large payloads, HAPs are able to provide localization and environmental information for other wireless systems at lower layers, while performing surveillance to ensure safe and secure operation of the architecture, as well dedicating wireless power transfer to ensure a better quality of charging for low-endurance LAPs.

- **LAP layer:** Unlike the HAPs with their quasi-stationary positions, LAPs can fly with relatively random or optimally distributed locations to offer temporary or localized capacity with low propagation delay. It is possible for LAPs to deliver very small cells of hundreds of meters in diameter, creating the possibility of providing ultra-high capacity density communications for temporary events or disaster relief. They are mainly responsible for local network optimization in the integrated architecture through functioning as either aerial users or flying base stations in the sky according to their missions [9]. The LAPs, if needed, can also operate in a swarm through mutual cooperation to form a self-organized networks, linking with mmWave or free space optics (FSO). However, flying LAPs have a limited amount of on-board energy (the battery-powered LAPs are generally expected to work from dozens of minutes to several hours, while the solar power enabled LAPs may last longer). Thus, when designing the LAP layer in the system, the improvement of energy efficiency of LAPs requires careful consideration such as exploiting trajectory optimization, energy harvesting, etc. Besides, the optimal altitudes need also to be analyzed when deploying LAPs while considering the impact of both distance and LoS probability.

- **Ground layer:** The terrestrial network system is the main part of the interworking architecture for providing wireless coverage in the conventional core areas such as the metropolis. In these regions, the high performance requirements from massive amount of devices are often supported by rich and complex infrastructures, including macro and small cells, transport networks, and so on. There are three principal enabling technologies for 5G terrestrial networks, i.e., ultra densification, mmWave and massive multiple input multiple output (MIMO). However, to ensure the goal of global access to the Internet for all, several inevitable shortcomings have appeared, such as cost and interference for ultra densification, high path loss at the mmWave band, and the computational burden associated with massive MIMO. Fortunately, in this

[3]Latency is made up of a number of components, dominated by protocol delay and propagation delay. HAPs can provide service to a coverage area up to 200 km radius, resulting in a propagation round trip time of 1.5 ms. In the case of a HAP based system, anywhere in the coverage area can be reached in a single hop. However, the same area served terrestrially will have to rely on the core network and transmission through multiple nodes, each introducing additional protocol delay (protocol delay is generally 1-5 ms per node, mainly caused by the signaling and framing). Thus, the terrestrial system will tend to have a higher delay than the HAP system for end-to-end transmissions of greater than 20 km.

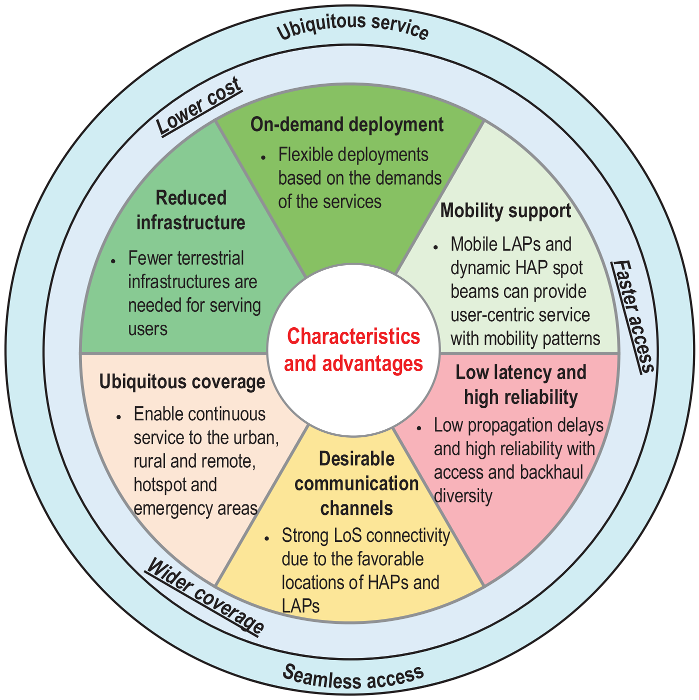


Fig. 2. Characteristics and advantages of the integrated air-ground network system.

integrated architecture, the terrestrial networks can leverage the power from the other two aerial layers to relieve the aforementioned issues.

- **Centralized orchestrator:** The central controller, based on SDN [10], will act as the brain of the system at the upper level to manage the whole network and incorporate the cross-tier segments of the architecture. Considering different segments have distinct characteristics, in addition to a global controller in upper layer for the management of the whole system, three separated SDN controllers in lower layer are dedicated to the corresponding segment for local network optimization. That is to say, the local SDN controllers perform fine-grained control, while the upper-tier global SDN controller conducts coarse-grained control. In particular, the orchestrator will play an intelligent role from three aspects: infrastructure, control, and application layers. From the perspective of infrastructure layer, computing, storage and communication resources from different segments will be processed by the controller through a virtualized cloud center. From the angle of control layer, the orchestrator will perform distributed decision making and coordination for the abstracted information in the system, such as beam steering of HAPs, movement control and deployment of LAPs, and resource block allocation in terrestrial base stations. From the application layer perspective, a variety of Internet access services and network management functions can be identified according to the instruction from the orchestrator, such as users' request reply, traffic classification, and dynamic route adjustment. In addition, the orchestrator will establish logical connections with the cross-tier segments to send control messages and to receive feedback information.

In summary, each segment has its own role to play in the architecture while each can compensate the others at the same time. Through interworking, the superiorities from both the sky and ground segments can be exploited. Access and backhaul diversities make the integrated network be capable of delivering a highly reliable connection, achieving ubiquitous coverage and seamless access for users in a real sense. From the holistic system perspective, *the HAP layer is for wide area coverage, and the LAP layer is for local network optimization while the ground layer is for core dense site service*. Moreover, our proposed network architecture will be a highly integrated system due to the fact that HAPs and LAPs have strong compatibility with the current cellular networks. Furthermore, since the cells provided by the three layers form contiguous coverage while the overlap between the cells is limited, the extra overhead with the integrated architecture is relatively small. As shown in Fig. 2, with the proposed integrated network architecture, several benefits can be achieved including *wider coverage, faster access and lower cost*.

IV. Key Enabling Technologies

In this section, we briefly present an overview of several key enabling technologies that are required to efficiently sustain the integrated air-ground networks. These technologies are introduced in four aspects, including *infrastructure design, network connectivity, layers interworking, and traffic identification*.

A. Aerial Platforms-Infrastructure Design

Since the terrestrial infrastructure has been well studied in existing works, here, we mainly discuss some design considerations for the aerial platforms, with the primary ones being: lightweight material structures, energy supply, and onboard communications payload. To improve the reality and durability of the aerial platforms, especially for the HAPs, the envelope material should have low weight, low permeability to lifting gas, high strength and ability to withstand damage, etc. Fortunately, with the development of advanced materials, these visions have been gradually achieved in recent years, which has resulted in HAPs being actively considered as viable technology again. The choice of energy source is another fundamental issue. Solar power coupled with energy storage has been regarded as primary means of providing energy for HAPs since they have large surfaces suitable to accommodate the solar panel films [6]. For the LAPs, advanced rechargeable batteries such as lithium-sulfur or regenerative fuel cell (RFC) may become the promising enabling technologies in the coming years. In terms of the communications payload, the antenna subsystem is one of the key components, in which phased array antennas are installed for the HAPs to produce the spot beams while tiny antennas, producing a single cell, are suitable for the size constrained LAPs to save space for other peripherals.

B. Backhaul Delivery-Network Connectivity

In the integrated air-ground network system, terrestrial infrastructure can utilize wired backhaul links, often fiber optics; whereas the aerial platform communications must exploit the wireless links. For HAP networks, mmWaves and FSO are more promising options for supporting long-range HAP-ground and inter-HAP links, owing to their highly directional beams and LoS paths, thereby providing desirable capacity backhaul in many regions of the world [6]. However, because link outage of mmWaves and FSO are caused primarily by rain attenuation and heavy cloud, such links may not be used in practice in some tropical countries due to the heavy and frequent rainfall. On the other hand, for LAPs with medium range and more limited capacity requirements, one could rely on the more economical sub-6GHz technologies like LTE to provide backhaul connectivity. In addition, satellite communications could be also integrated into the system as a complementary extra segment for situations where aerial and terrestrial communication infrastructures are not available, providing geolocation information and a backhaul alternative. However, it is worth mentioning that such a solution is not suitable for delay-sensitive applications due to the large latency from the satellites.

C. SDN/NFV-Layers Interworking

SDN and network function virtualization (NFV) have been extensively researched for use in terrestrial cellular networks [4]. In fact, through leveraging the concepts of software and virtualization, they are also being considered as key enabling technologies for more flexible integration and interworking of the air and ground segments. For example, during the operation of the integrated system, UAVs (e.g., LAPs) are required to seamlessly fly into the network during their activity and seamlessly disassociate when their service duration is over, which requires a high degree of network reconfigurability. Since NFV allows a programmable network structure, seamless integration of UAVs into the system will become available. Furthermore, through programming the hardware, NFV allows general UAVs to be used to perform particular network functions such as network gateways, which can reduce the operational expenditure by sharing available network resources [6]. On the other hand, owing to frequent changes of the network configuration, UAV networks need to be more fault tolerant. By abstracting the network and separating the control plane from the data plane, SDN introduces logically centralized control with a global view, which may be utilized to control and update the network flexibly to enhance the ability of the network fault tolerance and reduce scheduling delay.

D. Machine Learning-Traffic Identification

To reap the benefits of the integrated air-ground networks for practical telecommunication applications, various traffic requirements of the use cases need to be identified such as latency, efficiency, reliability, interference, etc. In this regard, machine learning enabled schemes are seen as a useful tool for handling these issues. For instance, in a large-scale UAV networks, constantly communicating with a remote node can introduce signaling delays. To reduce such delays, one can rely on on-device machine learning or edge artificial intelligence (AI), such as federated learning, to store a particular task in a distributed fashion across the UAVs and collectively solve the optimization problem [11]. This in turn enables a large number of UAVs to collaboratively allocate their radio resources in a decentralized way, thus reducing wireless congestion and latency. Besides, when cellular-connected UAVs establish LoS connectivity with terrestrial base stations, mutual interference among them as well as to ground users become severe. To address this challenge, deep reinforcement learning algorithms based on echo state network cells can be implemented on each UAV in order to learn the optimal path, transmission power level, and cell association vector at different locations, which enable UAVs to adjust their beamwidth tilt angle and path to minimize the interference on terrestrial networks [12]. In addition, for some multimedia streaming applications, convolutional neural networks (CNNs) can be adopted for allowing cache-enabled UAVs to store common data files since CNNs can extract and store the common features of the data files that are requested by different users [11].

V. Potential Applications and Case Studies

In this section, we introduce several potential application scenarios for the proposed integrated air-ground heterogeneous network architecture. Then, a case study is given to demonstrate the performance gain with the integrated architecture.

A. *Potential Scenarios for Enhancing 5G Applications*

Since conventional urban/suburban areas are expected to be well served based on the forthcoming 5G deployment, here, we mainly follow with interest the potentially underserved or hard-to-reach districts in which the aerial platforms can be used as an integrated part of networks to inject additional capacity and expand the coverage. As shown in Fig. 3, three typical scenarios are introduced, including *hotspot, emergency, rural and remote areas*.

Specifically, for some hotspot areas, flexible LAP base stations can be fast dispatched in corresponding areas to provide enhanced capacities for users. In terms of those unexpected emergency cases, through leveraging the aerial networks in the integrated system, low-altitude UAVs can be used to deliver emergency response to improve resilience of wireless networks. At the same time, the HAPs can establish new specific spot beams to support additional coverage. For rural and remote areas, if aided by the integrated system, HAPs are capable of bridging the vast digital divide in these regions, since they can stay in the

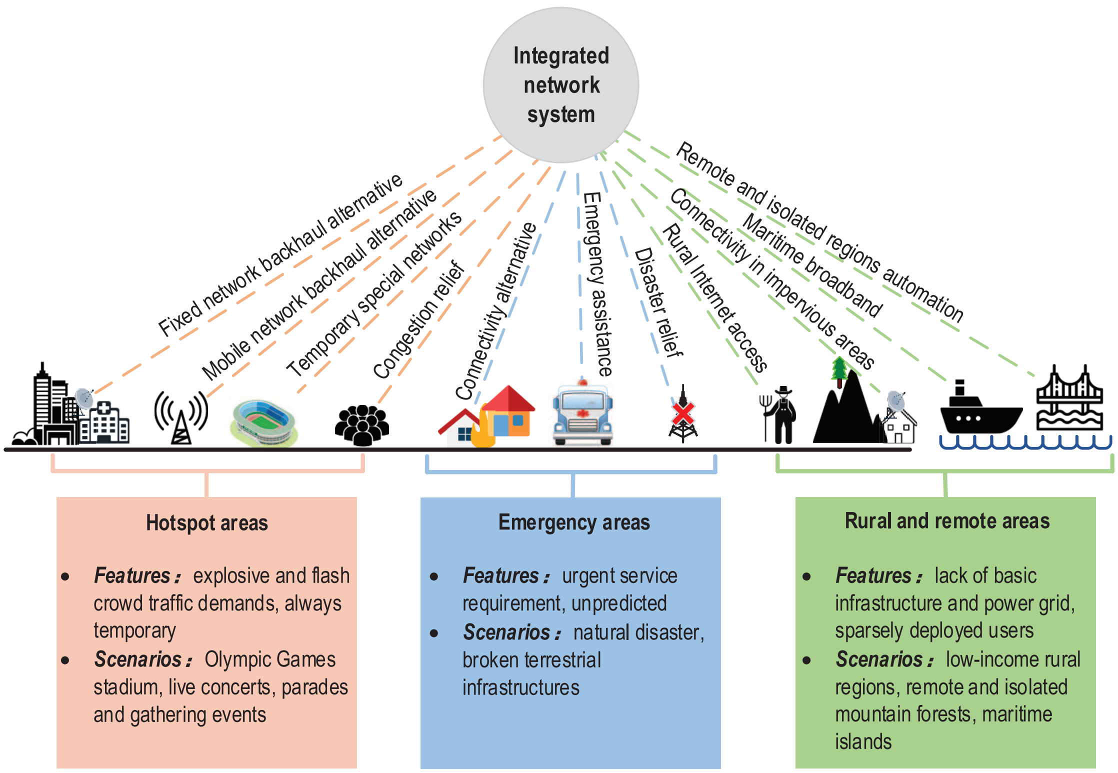
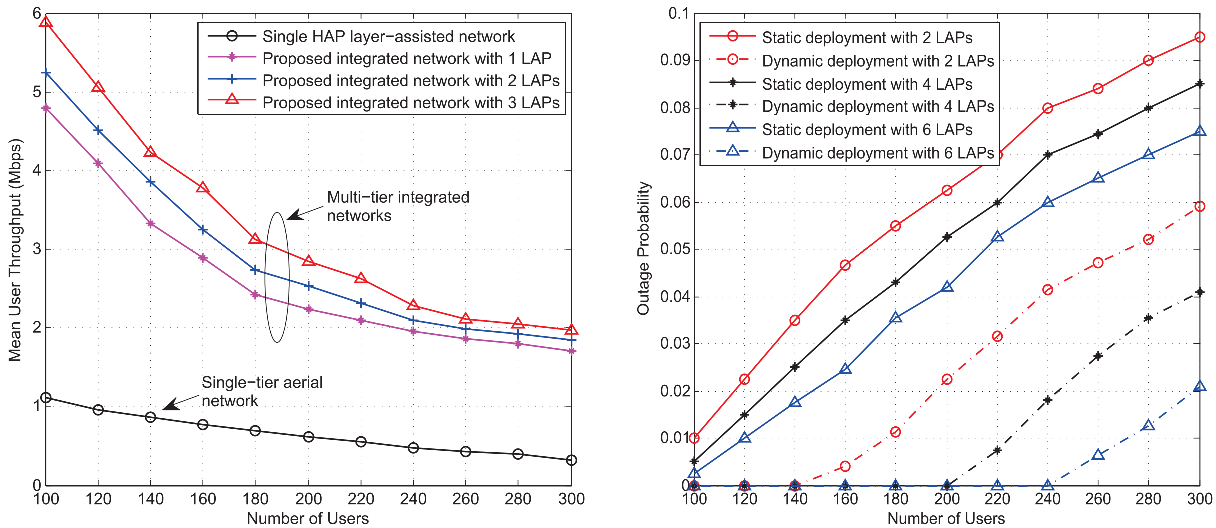


Fig. 3. Potential scenarios where the integrated air-ground network system can further enhance the applications of conventional terrestrial networks.

stratosphere to provide wide-area coverage, removing the need for large numbers of terrestrial masts and their associated infrastructures.

B. Case Study

In this section, we investigate the effectiveness of the proposed integrated air-ground network architecture and evaluate the system performance in terms of user throughput and outage probability. We consider a HAP located at altitude of $h_{HAP} = 20\ km$ above ground, serving a 30 km radius coverage area. LAPs are located inside the same service area at altitude of $h_{LAP} = 1\ km$ along with a three-sector macro cell placed at the center of the service area using a common frequency band. The system uses a carrier frequency of $f_c = 2.6\ GHz$ with $B = 20\ MHz$ bandwidth for a downlink transmission. HAP and LAPs path loss are modelled based on the free space path loss model while that is a 3GPP path loss model for the macro cell. The transmit power for HAP, LAPs and terrestrial base station are $37\ dBm$, $25\ dBm$ and $40\ dBm$, respectively. The noise power is $N_0 = -130\ dBm$. In order to illustrate the benefits bringing by the flexibility and mobility of LAPs, as in [13], two types of scenarios are considered: 1) static LAP deployment, 2) and dynamic LAP deployment.



(a) (b)

Fig. 4. Case study with static and dynamic LAP deployment: (a) static scenario, mean user throughput for standalone HAP-assisted network and multi-tier integrated air-ground networks with variation of the number of users, and (b) user outage probabilities for dynamic and static usage of LAPs versus different number of users.

Static LAP deployment: At first, we consider the static scenario in which the LAPs do not move or change their positions after deployment inside a HAP cell to serve the downlink users in the presence of one terrestrial base station. Fig. 4a illustrates the mean user throughput versus the number of users in the system. The mean user throughput is quantified after several simulation iterations to obtain the consistent results by assuming a user has maximum signal-to-interference-plus-noise ratio (SINR) which is $22\ dB$ in the system. It indicates the possibly achievable performance upper bound with the ideal case given the efficient interference control mechanism. As can be observed in the figure, the performances of the proposed integrated HAP-and-LAPs-aided heterogeneous network obviously outperform that of single-tier HAP-assisted cellular network. The reason is that with the incorporation of both HAP and LAPs, the probability for associated users experiencing LoS will be higher than just leveraging standalone HAP layer to assist the terrestrial network. Moreover, increasing the number of LAPs will further improve users' capacity due to the enhanced coverage. This demonstrates a multi-tier UAV-aided cellular network (i.e., integrated HAP-LAP-terrestrial network) exceeds the performance of a single-tier UAV-assisted network (i.e., HAP-terrestrial network).

Dynamic LAP deployment: In dynamic scenarios, we assume that the LAPs can further slightly adjust their positions over the associated service areas and transmit from a more efficient geographical location which we hereinafter refer to the local center point. Each center point represents the location of mean value of positions for all its previous associated users of a LAP. By moving to the local center point, the system performance of the corresponding service areas for the LAP will be improved due to the decrease in the cumulative communication distance which can increase the coverage probability of the downlink users. In Fig. 4b, the user outage probability (i.e., the probability that the instantaneous SINR falls below a threshold) versus the number of users is given. It can be observed that, compared with the static LAP deployment, the dynamic usage of LAPs has better system efficiency with decreasing in the user outage probability.

VI. Challenges and Open Issues

In spite of the potential, the research on air-ground heterogenous networks with integrating HAPs and LAPs is still in its infancy, where many key research issues are still open. In this section, some challenges and main research topics are discussed.

Resource allocation and interference management: With aerial and terrestrial segments integrated in the hierarchical network system, resource allocation and interference management become more challenging by virtue of the highly dynamic network environment and multi-dimensional heterogeneity in resources and services. Thus, there is a need for designing efficient scheduling techniques to dynamically manage various resources from both aerial and terrestrial networks including energy, bandwidth, transmit power, etc. Besides, in the case of coexistence of multiple communication systems, apart from co-channel interferences between different segments, severe inter-carrier interference at higher transmission frequencies (e.g., mmWave) will be caused by Doppler shift due to mobility of UAVs. Therefore, inherent dynamics of the networks such as time-varying interference, varying traffic patterns, and mobility of the UAVs, should be captured when operating resource management and spectrum sharing. To this end, optimizing the heights and intensities of various tiers of UAVs and coordination among UAVs may be useful [14].

Cross-tier interworking among different segments: Cross-tier networking architecture is supported by various communication protocols, and each layer comprises vast devices with different interfaces for configuration and control. Although the SDN is explored to enable unified control of the system, it is still not easy to achieve seamless convergence of multiple radio access technologies and network types. Thus, it is desirable to design some cooperative incentives between aerial and terrestrial segments. Dedicated cross-layer protocols and interworking mechanisms are also needed to ensure link reliability.

Handover and user/cell association: Handover in the integrated networks will be more frequent due to three factors: 1) movement of the terminal users, 2) flight dynamics of LAPs, and 3) dynamic spot beams of HAPs. Therefore, efficient adaptive algorithms are necessary for a user to achieve fast handover when switching from the aerial networks to the terrestrial networks and vice versa. On the other hand, although the integrated system provides multi-connectivity options, jointly considering the mobility and constraint in flight time of UAVs, user or cell association problems become intractable.

In this regard, advanced mathematical tools such as optimal transport theory may be useful for these notoriously difficult optimization problems owing to its much deeper fundamental analysis of network performance optimization [3].

Privacy and public safety: The regulation to exploit aerial platforms for commercial use in cellular networks is still underway. Nonstandard and illegal deployment or utilization of UAVs may lead to serious public safety hazard [15]. Thus, suitable safety and surveillance schemes are urgently needed. Moreover, due to the wireless transmission properties of the aerial networks, they are particularly vulnerable to malicious attacks. Thus, safeguard strategies or protocols are of paramount importance. Besides, SDN controllers are mainly responsible for managing the system, protecting the SDN controllers from different cyber attacks is also needed in integrated networks.

Other open issues include but not limited to air-ground channel modelling, aerial platforms deployment and trajectory planning, energy consumption and efficiency, etc. Due to the page limit, we omit the detailed discussions about them. However, these research topics also deserve to be further studied in the future.

VII. Conclusion

In this article, we have proposed a hierarchical air-ground network architecture to exploit the advantages of integration of HAP, LAP and ground segments, to support ubiquitous communication services in various scenarios efficiently and cost-effectively. The designed system is envisioned to be deployed as a complementary solution to broaden the applications of current terrestrial cellular networks for underserved scenarios and hard-to-reach areas. The basic networking architecture and main enabling technologies have been introduced. Furthermore, the potential advantages, applications and challenges of jointly integrating multi-tier aerial platforms into future wireless networks have been also discussed. This article sheds light on cross-tier interaction between aerial and terrestrial networks and helps to accelerate the pace of development and related research about integrated air-ground networks.

References

[1] J. Wu, S. Guo, H. Huang, W. Liu, and Y. Xiang, “Information and Communications Technologies for Sustainable Development Goals: State-of-the-Art, Needs and Perspectives,” *IEEE Commun. Surveys & Tutorials*, vol. 20, no. 3, 2018, pp. 2389–2406.

[2] Y. Zeng, R. Zhang, and T. J. Lim, “Wireless Communications with Unmanned Aerial Vehicles: Opportunities and Challenges,” *IEEE Commun. Mag.*, vol. 54, no. 5, May 2016, pp. 36–42.

[3] M. Mozaffari, W. Saad, M. Bennis, Y.-H. Nam, and M. Debbah, “A Tutorial on UAVs for Wireless Networks: Applications, Challenges, and Open Problems,” *IEEE Commun. Surveys & Tutorials*, DOI: 10.1109/COMST.2019.2902862, 2019.

[4] I. Bor-Yaliniz and H. Yanikomeroglu, “The New Frontier in RAN Heterogeneity: Multi-Tier Drone-Cells,” *IEEE Commun. Mag.*, vol. 54, no. 11, Nov. 2016, pp. 48–55.

[5] D. Grace, M. H. Capstick, M. Mohorcic, J. Horwath, M. B. Pallavicini, and M. Fitch, “Integrating Users Into the Wider Broadband Network via High Altitude Platforms,” *IEEE Wireless Commun.*, vol. 12, no. 5, Oct. 2005, pp. 98–105.

[6] X. Cao, P. Yang, M. Alzenad, X. Xi, D. Wu, and H. Yanikomeroglu, "Airborne Communication Networks: A Survey," *IEEE JSAC*, vol. 36, no. 9, Sep. 2018, pp. 1907–1926.

[7] A. Mohammed, A. Mehmood, F.-N. Pavlidou, and M. Mohorcic, "The Role of High-Altitude Platforms (HAPs) in the Global Wireless Connectivity," *Proc. IEEE*, vol. 99, no. 11, Nov. 2011, pp. 1939–1953.

[8] I. Bor-Yaliniz, M. Salem, G. Senerath, and H. Yanikomeroglu, "Is 5G Ready for Drones: A Look into Contemporary and Prospective Wireless Networks from a Standardization Perspective," *IEEE Wireless Commun.*, vol. 26, no. 1, Feb. 2019, pp. 18–27.

[9] M. Mozaffari, A. T. Z. Kasgari, W. Saad, M. Bennis, and M. Debbah, "Beyond 5G with UAVs: Foundations of a 3D Wireless Cellular Network," *IEEE Trans. Wireless Commun.*, vol. 18, no. 1, Jan. 2019, pp. 357–372.

[10] D. Kreutz, F. M. Ramos, P. Verissimo, C. E. Rothenberg, S. Azodolmolky, and S. Uhlig, "Software-Defined Networking: A Comprehensive Survey," *Proc. IEEE*, vol. 103, no. 1, Jan. 2015, pp. 14–76.

[11] U. Challita, A. Ferdowsi, M. Chen, and W. Saad, "Machine Learning for Wireless Connectivity and Security of Cellular-Connected UAVs," *IEEE Wireless Commun.*, vol. 26, no. 1, Feb. 2019, pp. 28–35.

[12] U. Challita, W. Saad, and C. Bettstetter, "Interference Management for Cellular-Connected UAVs: A Deep Reinforcement Learning Approach," *IEEE Trans. Wireless Commun.*, vol. 18, no. 4, Apr. 2019, pp. 2125–2140.

[13] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Unmanned Aerial Vehicle With Underlaid Device-to-Device Communications: Performance and Tradeoffs," *IEEE Trans. Wireless Commun.*, vol. 15, no. 6, June 2016, pp. 3949–3963.

[14] B. Li, Z. Fei, and Y. Zhang, "UAV Communications for 5G and Beyond: Recent Advances and Future Trends," *IEEE Internet Things J.*, vol. 6, no. 2, Apr. 2019, pp. 2241–2263.

[15] G. Ding, Q. Wu, L. Zhang, Y. Lin, T. A. Tsiftsis, and Y.-D. Yao, "An Amateur Drone Surveillance System Based on the Cognitive Internet of Things," *IEEE Commun. Mag.*, vol. 56, no. 1, Jan. 2018, pp. 29–35.

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BIOGRAPHIES

Junfei Qiu (dr.junfei.qiu@gmail.com) received his B.S. degree from Wuhan University of Science and Technology, Wuhan, China, in 2013, and his M.S. degree from College of Communications Engineering, Nanjing, China, in 2016. He is currently working toward a Ph.D. degree at University of York, York, United Kingdom. His research interests include UAV communications, blockchain, and machine learning.

David Grace (david.grace@york.ac.uk) received his Ph.D. degree from University of York in 1999. Since 1994 he has been in the Department of Electronics at York, where he is now Professor (Research) and Head of Communication Technologies Research Group. He is also Director of the Centre for High Altitude Platform Applications, an interdisciplinary research centre at York. His current research interests include high altitude platform and low altitude drone based communications, AI-enabled dynamic spectrum access and interference management. He is a former chair of IEEE Technical Committee on Cognitive Networks.

Guoru Ding (dr.guoru.ding@ieee.org) is an associate professor in College of Communications Engineering, Nanjing, China. His research interests include cognitive radio networks, massive MIMO, machine learning, and big data analytics over wireless networks. He was awarded as the Excellent Young Scientist of Wuwenjun Artificial Intelligence in 2018, the Alexander von Humboldt Fellowship in 2017 and the Excellent Doctoral Thesis Award of China Institute of Communications in 2016. He is now an Associate Editor of IEEE Transactions on Cognitive Communications and Networking. He served as a Guest Editor of the IEEE Journal on Selected Areas in Communications. (Special issue on spectrum sharing and aggregation in future wireless networks). He was a recipient of several Best Paper Awards from EAI MLICOM 2016, IEEE VTC 2014-Fall, and IEEE WCSP 2009, etc.

Muhammad D. Zakaria (mdz501@york.ac.uk) received the B.S. degree at Universiti Putra Malaysia, in 2014. He is currently pursuing the Ph.D. degree with the Department of Electronic Engineering, University of York. He was a Fellow with Universiti Sultan Zainal Abidin, under the Fellowship Scheme. His research interests include the high altitude platform (HAP)-based communication and coexistence with terrestrial networks.

Qihui Wu (wuqihui2014@sina.com) is a professor in College of Electronic and Information Engineering, Nanjing University of Aeronautics and Astronautics, China. From 2005 to 2007, he was an associate professor with the College of Communications Engineering, Nanjing, China, where he served as a professor from 2008 to 2016. His current research interests include the areas of wireless communications and statistical signal processing, with emphasis on system design of software defined radio, cognitive radio, and smart radio.